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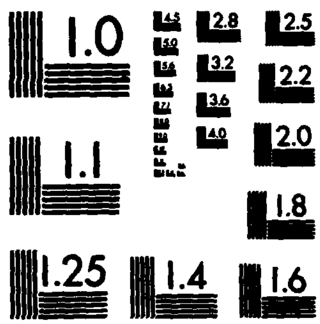

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FINAL REPORT
Joint Services Electronics Program
DAAG29-81-K-0024
April 1, 1981 – March 31, 1984

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

JUNE 1984

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

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EM Radiation Measurements

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is a final report on research conducted under the auspices of the Joint Services Electronics Program. Specific topics covered are: digital signal processing, parallel processing architectures, two-dimensional optical storage and processing, hybrid optical/digital signal processing, electromagnetic measurements in the time domain, and automatic radiation measurements for near-field and far-field transformations.

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June 1984

School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

TABLE OF CONTENTS

I. INTRODUCTION

This report combines the annual report on research carried out under Contract DAAG29-81-K-0024 during the period April 1, 1983 through March 31, 1984 and the final report for the total contract period April 1, 1981 through March 31, 1984. The research activities were concentrated in two areas: 1) Two-Dimensional Signal Processing and Storage, and 2) Theory and Applications of Electromagnetic Measurements.

The research in two-dimensional signal processing and storage focuses on four major areas which overlap and reinforce one another. Digital Signal Processing research deals with the theory, design, and application of digital signal representations and digital signal processing algorithms and systems. The research in Parallel Processing Architectures is concerned with hardware and software problems in the use of multiport memories and multiple microprocessors for high-speed implementations of signal processing algorithms. The Two-Dimensional Optical Storage and Processing research efforts have focused upon holographic storage of information in electro-optical crystals and upon digital signal processing operations that can be incorporated with storage and retrieval functions. Hybrid Optical/Digital Signal Processing is concerned with the theory, implementation, and application of combined optical and electronic digital signal processing techniques. Details of the research in this general area are given under Work Units Number 1 through 6.

The research in electromagnetic measurements is focused upon two major areas. Research in Electromagnetic Measurements in the Time Domain has centered on the development of new methodology for making time domain measurements. The work involves both theoretical and experimental investigations of the use of transient signals to measure the characteristics of materials and electromagnetic systems. Research in Automated Radiation Measurements for Near- and Far-Field Transformations has been concerned with assessing the accuracy of computed fields on the surface of lossy radomes and with compensating for probe effects when near-field measurements are made on arbitrary surfaces. Particular attention is devoted to spherical surfaces. This research is described under Work Units 7 and 8.

The report begins with a list of the work units and corresponding principle investigators. Then the most significant accomplishments during the three year contract period (in the judgement of the lab directors) are discussed in Section II. This is followed by a list of degrees granted to students who have worked on JSEP research during the three year contract period. Sections V and VI contain progress reports on each of the individual work units including a complete list of publications for the three year contract period.

II. LIST OF WORK UNITS AND PRINCIPAL INVESTIGATORS

The following is a list of work units and their corresponding principal investigators. Brief reports and a complete publication list for each work unit are given in Sections V and VI.

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE

1. Constrained Iterative Signal Restoration Algorithms
   R.M. Mersereau and R.W. Schafer

2. Spectrum Analysis and Parametric Modelling
   R.W. Schafer and R.M. Mersereau

3. Signal Reconstruction from Partial Phase and Magnitude Information
   M.H. Hayes

4. Multiprocessor Architecture for Digital Signal Processing
   T.P. Barnwell, III

5. Two-Dimensional Storage and Processing
   T.K. Gaylord

6. Hybrid Optical/Digital Signal Processing
   W.T. Rhodes

THEORY AND APPLICATION OF ELECTROMAGNETIC MEASUREMENTS

7. Electromagnetic Measurements in the Time Domain
   G.S. Smith

8. Automated Radiation Measurements for Near- and Far-Field Transformation
   E.B. Joy

III. SIGNIFICANT RESEARCH ACCOMPLISHMENTS (1981-1984)

The years covered by this final report have produced many useful and potentially important results. These results are documented in the theses, the conference presentations, the journal articles, the book chapters and the patents listed in this report. The following accomplishments are, in the judgement of the laboratory directors, of particular significance and worthy of special mention.

3.1 Development of Rigorous Coupled-Wave Theory of Grating Diffraction.

A rigorous coupled-wave theory of grating diffraction has been originated and developed by T.K. Gaylord working with M.G. Moharam. For the first time this new and powerful method allows the diffraction by gratings to be analyzed simply and without approximations. These grating structures are widely used in laser beam deflection, guidance, modulation, coupling, filtering, wavefront reconstruction, and distributed feedback in the fields of acousto-optics, integrated optics, holography, quantum electronics, signal processing, and spectrum analysis.

By expanding the electric field in terms of space harmonics and substituting it into the wave equation, an infinite set of second-order coupled-wave equations is produced. The state variables approach from linear systems theory has been applied to solving this set of equations. This results in closed-form expressions for the space harmonic fields in terms of the eigenvalues and eigenvectors of the differential equation coefficient matrix. By applying the electromagnetic boundary conditions, a set of linear algebraic equations is obtained. These may then be solved for the forward and backward diffracted fields outside of the grating.

The rigorous coupled-wave method of analysis is straightforward to implement numerically. It has been implemented on large computers and on minicomputers. Even though this method was published relatively recently, it has already been widely cited, used, and copied by university, governmental, and industrial laboratories.

As a side benefit, the rigorous coupled-wave theory has been used to evaluate in detail, for the first time, the previous approximations (neglect of higher-order waves, neglect of second derivatives of field amplitudes, neglect of boundary effects, neglect of dephasing, small modulation approximation, and large period approximation) that are inherent in previous approximate theories such as 1) multiwave coupled-wave theory, 2) two-wave second-order coupled-wave theory, 3) two-wave modal theory, 4) two-wave first-order coupled-wave theory (Kogelnik theory), 5) optical path method theory, 6) Raman-Nath theory, and 7) amplitude transmittance theory. The regimes of applicability for each of these approximate theories have now been established.

Specific applications in which the rigorous coupled-wave theory is currently being used include: optical digital parallel processing, acousto-optic signal processing, dielectric waveguide grating coupling, integrated optical spectrum analysis, and holographic head-up displays. References to publications on this work are given in Work Unit Number 5.

3.2 New Algorithms for Multi-Dimensional Fourier Analysis.

A discrete-Fourier transform (DFT) was discovered which relates a non-rectangularly sampled (e.g. on hexagonal grid) signal of finite extent to non-rectangular samples of its Fourier transform. Several algorithms have been developed to evaluate this DFT. One of these is a generalization of the Cooley-Tukey FFT algorithm which achieves its efficiency by replacing a computation over a lattice by similar computations over a series of sublattices. Existing algorithms for evaluating rectangular DFTs have been shown to be special cases of this general algorithm. With the discovery of a Chinese remainder theorem which could be applied to multidimensional lattices, it has been possible to generalize the prime factor algorithms and the Winograd Fourier transform algorithm. These algorithms have been proven to be optimal in terms of minimizing the number of arithmetic computations, but they are not simple to program. The key discovery which alleviated most of the programming difficulty was the observation that if the periodicity matrix (an integer matrix which defines the DFT) was expressed in a diagonalized form known as Smith's normal form, then the DFT could be performed using a row-column algorithm with two additional data permutations. Those interested in obtaining a copy of the programs should contact Professor R.M. Mersereau. It is expected that these algorithms should be useful in the design of frequency-domain beamformers, in the design and analysis of phased arrays, and in multi-dimensional spectrum analysis. See Work Unit Number 2 for references to publications on this work.

3.3 Optimal Multiprocessor Implementations of DSP Algorithms

Work Unit Number 4 has introduced a new conceptual framework and a new formalism for the description and manipulation of synchronous multiprocessor implementations of highly structured algorithms. This formalism has led directly to meaningful definitions for optimality and a number of associated techniques for the automatic generation of optimal multiprocessor implementations from intrinsically non-parallel representations. When applied in the context of systolic arrays, the result was a rigorous procedure for the generation and verification of systolic realizations from the underlying generic flow graph for the algorithm. This means that virtually any proposed systolic implementation can be quickly and rigorously verified, but, more importantly, it means that the set of optimal systolic implementations for the algorithm can be automatically generated. When applied in the area of SSIMD implementations, the result was a multiprocessor compiler for the automatic generation of the best achievable SSIMD realization. This compiler was implemented for the Georgia Tech DSP Multiprocessor Computer, but it can be easily configured to generate code for a large class of discrete component and VLSI based multiprocessors. The most important result of the research, however, was derived from the recognition of a new class of multiprocessor realizations. These realizations, which were named Cyclo-static realizations, have some of the features of both SSIMD and systolic solutions, but are generally more flexible and easier to automate than either. The cyclo-static approach results in a very large and previously unrecognized class of optimal multiprocessor implementations which can be automatically generated and which can be used in the context of either discrete component or VLSI systems. The cyclo-static approach has great promise for the design of optimal multiprocessor systems.

IV. DEGREES GRANTED (1981-1984)

The following students have either received support from JSEP funds or have worked on problems in JSEP supported work units with Institute or fellowship support.

Doctoral Degrees

L.N. An - June 1981
Thesis: "The Eccentrically Insulated Circular Loop Antennas and the Horizontal Circular Loop Antennas Near a Planar Interface"
C.C. Guest - December 1983
Thesis: "Holographic Optical Digital Parallel Processing"
A. Guessoum - June 1984
Thesis: "Fast Algorithms for the Multidimensional Discrete Fourier Transform"

Master's Degrees

C.F. Earnest - June 1981
R. Marucci - June 1981
Thesis" "Signal Recovery from the Effects of a Non-Invertible Distortion Operator"
T.G. Picard - June 1981
B.E. Eisenman - December 1981
K. Clark - December 1981
A. Katsaggelos - December 1981
W. Scott - March 1982
J. Guske - September 1982
A Scarasso - June 1982
P.A. Maragos - June 1982
Thesis: "On the Adaptive Predictive Coding of Digital Monochrome Still Images"
G.R. Scott - June 1982
Z.H. Tumeh - June 1983
K. Hsu - June 1983
S.J. Lim - December 1983
Thesis: "Generalization of One-Dimensional Algorithms for the Evaluation of Multidimensional Circular Convolutions and DFTs"

Bachelor's Degrees

M. Randolf - June 1981
E.W. Brown, III - June 1982

WORK UNIT NUMBER 1

TITLE: Constrained Iterative Signal Restoration Algorithms

PRINCIPAL INVESTIGATORS:

R.M. Mersereau, Professor
R.W. Schafer, Regents' Professor

SCIENTIFIC PERSONNEL:

J. Biemond, Visiting Associate Professor
C.C. Davis, Graduate Research Assistant (Ph.D. candidate)
C.F. Earnest, Graduate Research Assistant (M.S., June 1981)
J.H. Hansen, Graduate Research Assistant
A.G. Katsaggelos, Graduate Research Assistant (Ph.D. candidate)
R. Marucci, Graduate Student (M.S., June 1981)
A. Scarasso, Graduate Student (M.S., June 1982)

SCIENTIFIC OBJECTIVE:

The objective of this research is to study a broad class of iterative signal restoration techniques which can be applied to remove the effects of many different types of linear and nonlinear distortions through knowledge of signals. Specific attention is directed towards problems in deconvolution, reconstruction from projections, bandlimited extrapolation, and shift varying deblurring of images.

RESEARCH ACCOMPLISHMENTS:

Several of the techniques which have been investigated under this work unit are based upon iteration equations of the form

$$x_o(n) = \sum_{i=1}^{N} \lambda_i(n) * y_i(n)$$

$$\tilde{x}_k(n) = C[x_k(n)] \quad (1)$$

$$x_{k+1}(n) = \tilde{x}_k(n) + \sum_{i=1}^{N} \lambda_i(n) * (y_i(n) - D_i[\tilde{x}_k(n)]).$$

where the N signals $y_i(n) = D_i[x(n)]$ are distorted versions of a desired signal, $x(n)$, $C[\cdot]$ is a constraint operator, and the $\lambda_i(n)$ are linear operators which can be chosen to improve the convergence properties of the iteration. One important application of this iterative scheme is when the distortion operators are linear (i.e. convolutions) corresponding to photographic blurs when the signals are two-dimensional. Previous work on this problem concentrated on the case N=1. If several blurred versions of the same image are obtained with different blurring operators, however, we showed in [1] that improved performance over the N=1 case could be obtained. This was particularly true in situations where the frequency responses of the blurring operators have zeros. In these cases it is possible to restore the original signal if at least one of the frequency responses is zero at each frequency. Thus, information which is missing in one signal is provided in another.

The M.S. thesis by Marucci [2] showed that the fixed-point iteration for constrained deconvolution given in (1) for the case N=1, based on Van Cittert's unconstrained iteration is equivalent to a functional minimization. A more rapidly converging algorithm results by using the conjugate gradient algorithm to perform this minimization. The conjugate gradient approach is also directly applicable to the iterative implementation of a 2-D recursive digital filter which has been recently introduced by Dudgeon. These results are summarized in [3].

A major advantage of the iterative approach is that the equations involved in the signal restoration algorithm are formulated in terms of the distortion operator itself rather than its inverse. This is particularly important in problems where the inverse operator either does not exist or is difficult to determine and implement. This is the case for example in where the distortion is linear but shift-variant. We have begun to explore the application of iterative algorithms for shift-varying distortions such as might be encountered in non-uniform motion blur. Promising preliminary results were obtained in [2] but the extensive computational burden of the processing has delayed applying these techniques to images.

One potential concern with the use of these iterative algorithms for deconvolution is the effect of noise on the restoration. In the absence of constraints on the class of feasible solutions, the iteration in (1) will converge to the inverse filter solution if it exists. Inverse filters, however, are known to perform badly in the presence of broadband noise. An ad hoc procedure which improves performance is to prefilter the data to enhance the signal-to-noise ratio and then to incorporate this filter into the distortion to be removed. As a result of the nonlinear constraints, this approach works well. However, it is not optimal and it does not make use of the statistical properties of the signal and the noise.

One approach for incorporating statistical information is motivated by the similarity between our iterative equation and a Kalman filter. Specifically, if we assume that our image obeys a model of the form

$$x(m,n) = c(m,n)**x(m,n) + w(m,n) \qquad (2)$$

where $w(m,n)$ is white noise and if we further assume that we observe the signal $y(m,n)$ given by

$$y(m,n) = b(m,n)**x(m,n) + v(m,n) \qquad (3)$$

where $b(m,n)$ represents a linear distortion and $v(m,n)$ represents additive noise, then the minimum mean squared error estimate of $x(m,n)$ is given by

$$\tilde{x}(m,n) = c(m,n)**\tilde{x}(m,n)+\lambda(m,n)[y(m,n)-b(m,n)**c(m,n)**\tilde{x}(m,n)] \qquad (4)$$

The first term on the right side of this expression represents a prediction of $x(m,n)$ in terms of its neigboring samples. The predictor kernel, $c(m,n)$, incorporates prior information about the image. The second term represents the innovation (the unpredictable information) that is introduced by the observation $y(m,n)$. The quantity $\lambda(m,n)$ is known as the Kalman gain. The Kalman filter is typically implemented as a recursion. The samples of $x(m,n)$ are ordered and the operator $c(m,n)$ must make its prediction using only previously computed samples of $x(m,n)$. This requires a causal model for image formation which is difficult to justify on physical grounds.

Our iterative algorithm for solving the same problem takes the form

$$x_{k+1}(m,n) = C[x_k(m,n)]+\lambda(m,n)\left[y(m,n)-b(m,n)**C[x_k(m,n)]\right] \quad (5)$$

The outward similarity between this equation and (4) is striking, but the differences in implementation and philosophy between the two approaches are important. Specifically, note that the constraint operator functions as a predictive operator in the Kalman formulation. Furthermore, in the fixed-point iteration, the constraint *operator C need not be* a linear operator. More significantly, however, the operator C is not required to be causal which permits a non-causal image model to be used. On the other hand, by considering the fixed-point iteration as a form of Kalman filter, we can utilize statistical information about $x(m,n)$ and $v(m,n)$ to design C and the Kalman gain $\lambda(m,n)$. This allows the implementation of "soft" constraints. Preliminary results for a one-dimensional simulated motion blur with a signal-to-noise ratio of 20dB show an improvement of up to 7.5dB. In this initial work a non causal first-order linear predictive model for image was used. These results are described in [4,5].

The generalized iteration given in eq. (1) is also appropriate for the problem of recovering a multidimensional signal from its projections, a problem which occurs in computerized tomography and in spotlight mode synthetic aperture radar. For this problem the distortion operator D_i would consist of forming a projection at a particular orientation, followed by a back-projection in the same direction to restore the dimensionally of the signal.

Iterative solutions in the form of eq. (7) for this problem have been known for approximately fifteen years. The first of these was known as the Algebraic Reconstruction Technique (ART). With ART, each of the $\lambda_i(n)$ is chosen to be constant. The ART algorithm is slow and its failure to converge has been observed when the iteration is allowed to continue indefinitely. ART does, however, do a fairly good job of reconstructing the signal if the iteration is terminated after about ten iterations. We have proposed an extension to this algorithm in which the function $\lambda_i(n)$ is used as a filter to improve the rate of convergence. The analysis of this algorithm is continuing.

Another approach to deconvolutions was formulated in terms of the principle of minimum entropy. This approach is based upon the assumption that for impulse-type signals which have been blurred by convolution with an unknown impulse response, the impulses can be uncovered by forcing the signal to be concentrated in a few isolated locations (i.e. the locations of the impulses). (R.A. Wiggins, "Minimum Entropy Deconvolution," Geoexploration, 16, pp. 21-35, 1978). This technique leads to a set of nonlinear equations which must be solved iteratively. Initial results are not promising due to a tendency of the method to produce unstable models for the unknown distortion impulse response, and this line of research was not pursued.

The problem of extrapolating a bandlimited signal from known values of the signal has attracted considerable interest due to its implication in spectrum analysis. In the discrete case it has been shown by two different constructive methods that a finite set of samples of a bandlimited signal cannot be uniquely extrapolated. The methods of proof are perhaps of interest in their own right since they show how to construct a bandlimited sequence with an arbitrarily long interval of consecutive zero samples. This result was reported in [6].

PUBLICATIONS AND PRESENTATIONS:

[1] A.G. Katsaggelos and R.W. Schafer, "Iterative Deconvolution Using Several Different Distorted Versions of an Unknown Signal," Proc. 1983 Int. Conf. on Acoustics, Speech, and Signal Processing, Boston, pp. 659-662, April 1983.

[2] R. Marucci, "Signal Recovery from the Effects of a Non-Invertible Distortion Operator," M.S. Thesis, June 1981.

[3] R. Marucci, R.M. Mersereau, and R.W. Schafer, "Constrained Iterative Deconvolution Using a Conjugate Gradient Algorithm," Proc. 1982 IEEE International Conference on Acoustics, Speech, and Signal Processing, pp. 1845-1848, 1982.

[4] A.K. Katsaggelos, J. Biemond, R.M. Mersereau, and R.W. Schafer, "An Iterative Method for Restoring Noisy Blurred Images," Proc. 1984 ICASSP, pp. 37.2.1-37.2.4, 1984.

[5] A.K. Katsaggelos, J. Biemond, R.M. Mersereau, and R.W. Schafer, "An Iterative Method for Restoring Noisy Blurred Images," Circuits, Systems, and Signal Processing, vol. 3, no. 2, to appear, June 1984.

[6] M.H. Hayes and R.W. Schafer, "On the Bandlimited Extrapolation of Discrete Signals," Proc. 1983 Int. Conf. on Acoustics, Speech, and Signal Processing, Boston, pp. 1450-1453, April 1983.

[7] R.M. Mersereau, M.H. Hayes, and R.W. Schafer, "A Survey of Methods for Iterative Signal Restoration," Conf. Record, IEEE Int. Conf. on Communications, Pheladelphia, pp. 3G.4.1-3G.4.5, June 1982.

WORK UNIT NUMBER 2

TITLE: Spectrum Analysis and Parametric Modelling

SENIOR PRINCIPAL INVESTIGATORS:

R.W. Schafer, Regents' Professor
R.M. Mersereau, Associate Professor

SCIENTIFIC PERSONNEL:

J.E. Bevington, Graduate Research Assistant
E.W. Brown, III, undergraduate student
A. Guessoum, Graduate Research Assistant (Ph.D., June 1984)
S.J. Lim, Graduate student (M.S., Dec. 1983)
P.A. Maragos, Graduate Research Assistant
T.C. Speake, Graduate Research Assistant

SCIENTIFIC OBJECTIVE:

The objective of this research is to study and develop new techniques for spectrum analysis of one- and two-dimensional signals and to study the use of this analysis in the modelling of one- and two-dimensional signals.

RESEARCH ACCOMPLISHMENTS:

Nonrectangular Representatives for Images

A major portion of our JSEP effort over the past five years has been devoted to the development of efficient algorithms for the sampling and processing of multidimensional waveforms on arbitrary periodic lattices. The motivation for this work was threefold. First, it was known that sampling schemes such as 2-D hexagonal sampling were more efficient than rectangular sampling. Secondly, there were problems for which non-rectangular sampling was more ideally suited; e.g., in processing the signals received by a phase array with a hexagonal arrangement of elements. It was also felt that this would lead to a more complete understanding of rectangular sampling. The specific goals were to develop efficient procedures for the design and implementation of non-rectangular recursive and nonrecursive digital filters, for the interpolation of signals from one sampling lattice to another, and for the evaluation of sampled Fourier transforms.

Specific algorithms for the design of hexagonally sampled FIR filters were developed and shown to require fewer arithmetic operations than their rectangular counterparts. We showed that recursive filters for signals defined on arbitrary periodic lattices could be designed using existing design algorithms that the stability of these filters could be tested. The problem of interpolating signals from one sampling lattice to another was solved by generalizing a 1-D decimator/interpolator [1]. This algorithm requires a multidimensional up-sampler to an intermediate lattice, a digital filter, and a multidimensional down-sampler. An alternative method for interpolation using discrete Fourier transforms was also developed. A discrete Fourier transform (DFT) was discovered which relates a non-rectangularly sampled signal of finite extent to non-rectangular samples of its Fourier transform [3,4,5] and several algorithms were developed to evaluate this DFT. One of these was a generalization of the Cooley-Tukey FFT algorithm which achieves its efficiency by replacing a computation over a lattice by similar computations over a series of sublattices [3]. Existing algorithms for evaluating rectangular DFTs were shown to be special cases of this general algorithm. With our discovery of a Chinese remainder theorem which could be applied to multidimensional lattices, we were also able to generalize the prime factor algorithms and the Winograd Fourier transform algorithm [6]. These algorithms were proven to be optimal in terms of minimizing the number of arithmetic computations, but they were not simple to program. The key discovery which alleviated most of the programming difficulty was the observation that if the periodicity matrix (an integer matrix which defines the DFT) was expressed in a diagonalized form known as Smith's normal form [7], then the DFT could be performed using a row-column algorithm with two additional data permutations. These algorithms were programmed and have been made available to a number of research centers. The details of this work are contained in the Ph.D. thesis by Guessoum [9] and the M.S. thesis of Lim [10].

Application of Linear Predictive Models for Images

A basic premise upon which this research is founded is that for a sampled image there are regions in which there is a high degree of correlation between adjacent pixels or between clusters of pixels and that these regions have well-defined boundaries. As a consequence, different regions of the image may be defined by different local correlation characteristics (textures) and/or local average intensity levels. Boundaries between regions, therefore, are places where the local correlation and/or intensity levels change.

Correlation in a sampled image can be represented by how well a pixel value can be predicted from a linear combination of its neighboring pixels. More precisely, if the image correlation is very high, then the image samples may be linearly predicted with little error, whereas a low correlation implies that a linear predictor would generally produce a large error. If it is assumed that a pixel value may be accurately predicted from a weighted sum of its neighbors, then there is also an implicit assumption that the image approximately fits a two-dimensional auto-regressive model of the form:

$$x(m,n) = \sum_{Q}\sum a(k,\ell)\,x(m-k,n-\ell)+A+u(m,n) \tag{1}$$

where $u(m,n)$ is a random process with either known or assumed statistics and where Q is a set of integer pairs which defines a linear predictor mask. Assuming the validity of this model, the model parameters may be determined by minimizing the mean square prediction error

$$e(m,n) = x(m,n) - \sum_{Q}\sum a(k,\ell)\,x(m-k,n-\ell) - A \tag{2}$$

where A is a constant to account for a d.c. level within the image. The values of $a(k,\ell)$ and A which minimize E are given by the solution of a set of linear equations of the form:

$$\sum_{Q}\sum a(k,\ell)S(k,\ell) + AM^2 = S(0,0) \qquad (3a)$$

$$\sum_{Q}\sum a(k,\ell)R(k,\ell:i,j) + AS(i,j) = R(0,0:i,j) \qquad (3b)$$

where (k,ℓ) belong to the set of integer pairs Q, and

$$R(k,\ell:i,j) = \sum_{m}\sum_{n} x(m-k,n-\ell)\,x(m-i,n-j) \qquad (4a)$$

$$S(i,j) = \sum_{m}\sum_{n} x(m-i,n-j). \qquad (4b)$$

Note that $R(k,\ell):i,j)$ is in the form of a two-dimensional correlation function and that $S(i,j)$ is simply an average of the image samples and that both are computed over some region of the image.

The relationship between linear predictive analysis and the model given by (1) may be seen by noting that if $x(m,n)$ exactly satisfies the model then the optimum prediction coefficients will be identical to the corresponding coefficients in the model, and thus the prediction error, $e(m,n)$, will be identical to the model excitation $u(m,n)$. Therefore, if $e(m,n)$ is used for $u(m,n)$ in (1), the image samples, $x(m,n)$, will be reconstructed exactly if the difference equation is stable. In this sense, the representation of an image in terms of the prediction coefficients and prediction error is equivalent to its representation in terms of image samples.

It is possible to extend the image model in (1) so that it is nonstationary. For example, an LPC analysis can be applied to small regions of the image so that each region can be represented by its own set of prediction coefficients, average value, mean-square prediction error, and prediction error samples. Such an approach of "local" or "short space" linear predictive image analysis has been applied to a number of images and it has been observed that the largest prediction errors occur at what we might naturally call edges or boundaries between regions of uniform texture. The major features of an image appear to be represented in a rather prominent way by the results obtained from a short-space linear predictive image analysis.

We have studied the use of linear prediction for the coding of monochrome and color images and these results have been prepared for publication [11,12,13,14,15]. This work has illustrated the importance of a bias estimate in the adaptive predictive coding of images to account for the fact that photographic images do not have zero mean. High quality coded images were produced at less than one bit per picture element.

In many applications, the goal of image processing is to extract a labelled line drawing which depicts, in a stylized way, the objects and shapes present in an image. An example is automatic map drawing from aerial photos. Another example might be in pre-processing for a system which can report a list of interesting objects in a scene. To achieve this level of information reduction, it is necessary to segment the image into regions which are distinguished from one another by differing attributes such as color, gray level, or texture. Often the boundaries of such regions correspond to the boundaries of objects or at least to parts of objects. Thus, texture segmentation and boundary detection are essential to obtaining highly reduced representations of images which are the primitive inputs to a syntactical analysis system.

The problem of texture segmentation has been approached from two directions. One approach is to find edges and then collect the edges into region boundaries. A complementary approach is to group pixels with similar attributes into regions and then to identify boundaries with these regions. Each approach has its limitations. Simple edge detection schemes generally can be relied upon to give only portions or segments of the true boundaries and, therefore, missing parts must be filled in some sort of line or curve following algorithm. On the other hand, although "region growing" approaches will necessarily produce closed boundaries, the resulting boundaries are likely to be inaccurate. Ideally, the good features of the two approaches should be combined to improve performance. An approach based upon linear predictive analysis appears advantageous in this regard since the prediction error contains edge information and the parameter, A, represents the local average intensity or gray level.

We have conducted a preliminary investigation into the use of the predictor coefficients as features for identifying regions of distinct texture within an image using fairly standard approaches from statistical pattern recognition. The prediction error was used as a distance measure in a feature space of LPC coefficients [13]. Our desire to be able to evaluate the LPC parameters over homogeneous regions has also forced us to perform our analysis over regions with irregular shapes [13].

We have looked extensively into the use of the LPC error for the detection of edges between regions of homogeneous texture. If we restrict our attention to a 1-D scenario where we are given the sequence $\{y(n), 0 \leq n \leq N-1\}$ where

$$y(n) = \begin{cases} y_1(n) & n \leq k \\ y_2(n) & n > k \end{cases} \tag{2}$$

and where $y_1(n)$ and $y_2(n)$ are independent discrete-time Gaussian random processes, then we have shown that the maximum likelihood estimate of k can be found from the LPC errors in region 1 and region 2. Specifically k should be chosen to minimize

$$E(k) = \sum_{n=p}^{k} \left[\frac{e_1^2(n)}{\sigma_1^2} + \ln(\sigma_1^2)\right] + \sum_{n=k+1}^{N-p-1} \left[\frac{e_2^2(n)}{\sigma_2^2} + \ln(\sigma_2^2)\right] \tag{3}$$

In this equation p is the order of the predictor, $e_1(n)$ and $e_2(n)$ are the LPC error sequences from the two regions, and σ_1^2 and σ_2^2 are the variances of the two errors. This approach has been extended to the 2-D case [16]. In the generalization it is particularly important to constrain the shapes of the edges. Piecewise linear and 1st-order Markov constraints have both been used and both seem to work reasonably well.

Other

We have also begun looking at morphological representations for binary [17] and gray-level images. These representations allow images to be processed with various types of logical and nonlinear operations for which a well-defined theory can be developed. These representations seem to have some promise in image coding and image segmentation.

Some effort has also been expended in the preparation of two major tutorial publications [18,19].

PUBLICATIONS AND PRESENTATIONS

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WORK UNIT NUMBER 3

TITLE: Signal Reconstruction From Partial Phase and Magnitude Information

PRINCIPAL INVESTIGATOR:

M.H. Hayes, Assistant Professor

SCIENTIFIC OBJECTIVE:

Reconstructing a signal from only the phase or from only the magnitude of its Fourier transform are important problems which arise in a wide variety of different contexts and applications. Signal reconstruction from only magnitude information, for example, is a problem which naturally occurs in such diverse fields as crystallography, astronomy, and optics where the phase of an electromagnetic wave is either lost or impractical to measure, i.e., only intensity data is available. The ability to reconstruct a signal from only phase information, on the other hand, has potentially useful applications in such fields as seismology, ocean acoustics, radar and sonar signal processing, and image processing. Specifically, phase-only signal reconstruction techniques may be applied to the problems of deconvolution, time-delay estimation, system identification, spectral factorization, and phase unwrapping.

The long range goal of this research is to address some important questions and practical issues related to the phase-only and magnitude-only reconstruction problems for discrete multidimensional signals. Included in this work is an investigation into the importance of "amplitude" information in the representation of signals, the development of some new approaches for reconstructing a signal from its spectral magnitude, a study of the sensitivity of phase-only reconstruction algorithms to measurement errors and computational noise and, finally, an investigation into possible approachs for robust signal reconstruction in the presence of noise.

RESEARCH ACCOMPLISHMENTS:

As part of the long-range goal of this project, the representation of signals in terms of spectral amplitude and spectral angle was developed [2,6]. In particular, the spectral amplitude of a signal was defined to be equal to the magnitude of the Fourier transform of the signal which has a sign depending upon the Fourier transform phase. Specifically, the interval zero to 2π was divided into two sets, one containing angles from θ to $\theta+\pi$ and the other containing all the remaining angles. If the phase of the Fourier transform lies in the interval θ to $\theta+\pi$, then the amplitude is positive. Otherwise, the amplitude is taken to be negative. Spectral angle, on the other hand, was defined to be the phase of the Fourier transform modulo pi after subtracting off the bias θ. With such a representation, it was shown that a causality constraint is sufficient for a discrete-time signal to be uniquely specified in terms of its spectral amplitude of, in most cases, to within a scale factor by its spectral angle [2,6]. Although this uniqueness result may be easily extended to discrete samples of spectral angle, it was shown that for an arbitrary collection of spectral amplitude samples, a unique specification is not always guaranteed. Nevertheless, it was shown that it is always possible to find a set of N spectral amplitude samples which uniquely specify a causal sequence of length N. It was further shown that if M is large enough then the spectral amplitude of the M-point Discrete Fourier Transform of a causal sequence of length N is sufficient for its unique reconstruction. Finally, several iterative algorithms were investigated for reconstructing finite length sequences from spectral amplitude. Although the correct solutions were always obtained with these algorithms, no theoretical proof of convergence was found.

Following up on some earlier work concerned with the importance of the boundary values of a two-dimensional field in the phase retrieval problem, some generalizations of the conditions for off-axis holography were developed. Specifically, it has been shown that a two-dimensional discrete field may be reconstructed from the magnitude of its Fourier transform provided that the boundary values of x(m,n) are known [5]. However, since the boundary values may not always be known, it was of some interest to investigate techniques for determining these boundary values. Due to the observation that a given spectral magnitude function may not uniquely specify the boundary conditions, other constraints were investigated. Therefore, for two-dimensional signals with rectangular regions of support, the two-dimensional plane was divided into eight different regions consisting of four quarter planes and four semi-finite strips. It was then shown that if a single point source is located in any one of these quarter planes then it is possible to reconstruct the boundary values of this field from its autocorrelation function, i.e., from magnitude of its Fourier transform [3]. Consequently, it follows that it is possible to recursively reconstruct the entire field, x(m,n), for this particular geometry. Since this point source may be arbitrarily close to the region of support of x(m,n), this result relaxes the requirement imposed in off-axis holography where the point source must be separated by a distance roughly equal to the diameter of the image. Although the boundary values may not be recovered from a single point source in one of the semi-infinite strips, it was shown that if two of the semi-infinite strips contained a point source (again, the point sources may be arbitrarily close to the region of support of the image) then it is again possible to reconstruct the boundary values, and hence, the entire 2-D array from its autocorrelation [3].

Another component of the research goals of this work unit concerns the sensitivity of phase-only reconstruction algorithms to measurement error and computational noise. It has been observed that phase-only reconstructions are very sensitive to inaccurate phase measurements. Therefore, an investigation into some new techniques for reconstructing signals from noisy phase was undertaken [7]. Two approaches were considered. The first involved the addition of redundancy to the data. Consider, for example, the case in which more than one phase measurement is available at each frequency. In this case, the phase noise may be reduced by simply averaging the measured phase values. Tihs, in general leads to an improved reconstruction. In, on the other hand, extra phase measurements are available at different frequencies then one of two different approaches were considered. The first is to perform L reconstructions of N-point sequences when LN different phase samples are given. The average of these reconstructions was then taken. The second approach considered a least squares reconstruction of the signal from the redundant phase samples. In the absence of noise, both approaches give the same solution. When noise corrupts the phase measurements, although different reconstructions were obtained, the performance of the two approaches were similar.

The second approach considered for robust phase-only signal reconstruction was the incorporation of a priori information to define constraint sets on the set of admissable solutions. Specifically, an iterative approach was used which sequentially imposed constraints in the signal (time) domain and the transform (frequency) domain. The signal domain constraints consisted of a time-truncation or windowing operation which imposed the assumed time-limited constraint. In the transform domain, four different constraints were considered:

(1) The allowable phase values were bounded by some maximum deviations from the given noisy phase observation.

(2) The true transform magnitude was known along with the noisy phase values.

(3) Constraints (1) and (2) were combined.

(4) The same as (3) except the convex hull of the constraint set in (3) was used.

It was observed that methods (2) and (3) perform very well with most sequences showing a marked improvement over previous approaches (due, in part, to the extra information incorporated in the reconstruction).

Finally, using some of the mathematical machinery acquired in the development of some of the theoretical results related to this work unit, in a constructive proof it was shown that it is not possible to perform a unique band-limited extrapolation of a discrete time-limited sequence without any additional information or constraints [7].

PUBLICATIONS:

[1] M.H. Hayes, "Signal Reconstruction from Spectral Phase or Spectral Magnitude," in Advances in Computer Vision and Image Processing, Vol. 1, (T.S. Huang, Ed.) JAI Press, 1984.

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WORK UNIT NUMBER 4

TITLE: Multiprocessor Architectures for Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR:

T. P. Barnwell, III, Professor

SCIENTIFIC PERSONNEL:

C. J. M. Hodges, Research Engineer
D. A. Schwartz, (Ph.D. candidate)
S. H. Lee, (Ph.D. candidate)
M. J. T. Smith, (Ph.D. candidate)
P. Yue, (Ph.D. candidate)
K. Clark, Graduate Research Assistant
Z. H. Tumeh, Graduate Research Assistant
M. Randolph, Undergraduate Student

SCIENTIFIC OBJECTIVES:

The objective of this research is to develop techniques for the automatic generation of optimal and near-optimal implementations for a large class of Digital Signal Processing (DSP) algorithms on digital machines composed of multiple processors.

RESEARCH ACCOMPLISHMENTS:

This research is centered on the problem of generating highly efficient implementations for a large class of DSP algorithms using multiple programmable processors. This problem is fundamental to many areas of activity, including VLSI design; DSP implementations using arrays of state machines, signal processing chips, or microprocessors; and DSP implementations using networks of general purpose computers.

DSP algorithms are unique in the sense that they often are both highly computationally intense and highly structured. For this reason, it is often possible to achieve extremely efficient synchronous multiprocessor implementations in which the data precedence relations (that is to say the control functions) are maintained through the system synchrony, and every cycle of every arithmetic processor is applied directly to the fundamental operations of the algorithm. The basic goal of this research is to develop automatable techniques for the generation of such synchronous multiprocessor implementations from intrinsically non-parallel algorithm descriptions in such a way that the resulting implementations are both definably and meaningfully optimal. In short, we are developing multiprocessor compilers for DSP algorithms which can be used to generate optimal multiprocessor implementations for both the discrete component and VLSI environment.

Historically, this research has emphasized a set of techniques which we have named Skewed Single Instruction Multiple Data, or SSIMD, realizations [2][4]. SSIMD implementations are generally realized on synchronous multiprocessor systems composed of many identical programmable processors. In

SSIMD implementations, all of the processors execute exactly the same program using a computational mode in which the instruction execution times on the individual processors are skewed with respect to one another. SSIMD implementations have proven to have many desirable properties for DSP realizations. First, since all SSIMD implementations involve only one program, the problem of finding the best multiprocessor implementation reduces to the task of finding the single processor implementation which is best suited for use in a SSIMD environment. Second, given any single processor program suitable for SSIMD implementations, it is possible to compute bounds on the performance of the full multiprocessor realizations which use that program. These bounds include the SSIMD sample period bound, which is the minimum achievable time between the processing of input points; the SSIMD delay bound, which is the minimum achievable latency between the arrival on an input and the generation of the corresponding output; and the SSIMD processor bound, which is the minimum number of processors required to achieve the SSIMD sample period bound. Third, and more important, these bounds are not only easily computable, but also easily achievable. In particular, all SSIMD realizations which utilize fewer processors than the processor bound are perfectly efficient (processor optimal) in the sense that an N processor implementation is exactly N times faster than a one processor realization. Finally, the communications architecture required by SSIMD implementations is completely controllable through the specification of the delay (pipeline register) structure within the algorithm itself. For SSIMD realizations, it is always possible to realize the algorithm using a unidirectional nearest neighbor communications structure, but more complex communications architectures can also be used to advantage if they are available. SSIMD realizations have many advantages for DSP realizations, particularly when compared to such approaches as systolic arrays, wavefront processors, SIMD and general MIMD solutions. In particular, SSIMD solutions tended to be faster, more efficient, and easier to find than the competing techniques. It is fair to say that most of the important research results obtained in this work unit over the last three years have resulted from a systematic attempt to understand the nature of the advantages which seemed to be inherent in the SSIMD approach.

We now know that SSIMD realizations are a special case of a more general class of synchronous multiprocessor implementations which we have named Cyclo-static realizations. The important SSIMD results were all derived using a formalism which abstracted the concept of a program. A "program", in this context, is defined as sets of instructions for the control of arithmetic processors. We have now developed a separate representation which deals not with programs, but with algorithms. In particular, we have introduced a three level formalism which allows for the simultaneous description and manipulation of both the arithmetic and implementational aspects of a very large class of DSP algorithms [8][9]. The three levels of the formalism — called the graph theoretic level, the matrix level, and the link-list level — are all mathematically equivalent representations of the same information and theory. Three separate levels are used because each of the three formalisms is particularly appropriate to understanding or implementing different aspects of the theory. The graph theoretic level is most appropriate for conceptualizing the basic techniques and presenting the results. The matrix level is most appropriate to conceptualizing the associated computer automation procedures. And the link-list level is most appropriate to the actual computer realizations of the optimization techniques.

The algorithms addressed by this theory are those which can be described using fully-specified shift-invariant flow graphs. These graphs are similar to the more familiar shift-invariant signal flow graphs except that the nodes can contain any (linear or nonlinear) operators which can be realized by the processors to be used in the multiprocessor realization. Given such a flow graph, and given the operation timings for the constituent processor which is to be used in the multiprocessor implementation of the flow graph, it is possible to compute absolute bounds on the performance of the multiprocessor realization. In particular, three bounds can be computed. The sample period bound is the shortest sample period at which the algorithm may be implemented regardless of the number of processors used. The delay bound is the shortest achievable period between an input and a corresponding output. And the processor bound is the fewest processors which can be used to achieve the sample period bound. These bounds give rise to a very fine-grained definition of optimality. An implementation is said to be rate-optimal if it achieves the sample period bound. An implementation is said to be delay-optimal if it achieves the delay bound. And an implementation is said to be processor-optimal if it is either perfectly efficient (factor N speedup) or if it achieves the sample period bound using the number of processors specified by the processor bound.

The application of our new formalism to the SSIMD approach resulted in the development of a SSIMD compiler for signal flow graphs [14]. This compiler, which can be configured to generate code for a large class of discrete and VLSI multiprocessor machines, is currently configured to generate code for the eight-processor, LSI-11 based multiprocessor which has been designed and implemented as part of this research [2][15]. This compiler always finds a rate-optimal SSIMD implementation if it exists, and finds the best SSIMD implementation if it does not. Because the computation of the bounds generates such a wealth of information about the nature of the optimal implementations, it is fairly simple to find a rate-optimal solution if it exists. It is far less efficient to find the best sub-optimal solution if no optimal solution exists. So we have the rather odd situation that if an optimal solution exists, it is relatively easy to find, but if it does not, the less desirable sub-optimal solutions are difficult (require more computational resource) to find. SSIMD realizations are always processor-optimal, often rate-optimal, and seldom delay-optimal.

The application of our new formalism to the systolic approach resulted in a rigorous procedure for transforming shift-invariant flow graphs into systolic realizations [8][9]. This procedure is base on another performance bound, the static pipeline sample period bound, which is the shortest period at which the graph can be implemented under the systolic constraints. This entire procedure can be fully automated and constitutes a formal technique for both the generation and the verification of systolic implementations from both shift-invariant and shift-variant flow graphs. Because of the wide interest in systolic implementations, we expect these results to have considerable impact over the next several years. But more important, this procedure showed very clearly the fundamental relationship between SSIMD and systolic implementations. Whereas systolic implementations constitute a full parsing of the algorithm (graph) in space, the SSIMD approach constitutes a full parsing of the algorithm (graph) in time, followed by a mapping of time into space. Both the SSIMD and the systolic approach are limited special cases of synchronous multiprocessor implementations, and both have the virtue that they simplify the problem to the point at which it may be solved. In many ways, SSIMD is the better technique since it obtains better performance from essentially the same architectures. But both approaches have the disadvantage that, in simplifying the problem, they have overconstrained the resulting implementations and they do not always obtain optimal realizations.

The primary result of this research is really the observation that SSIMD and systolic realizations are not mutually exclusive techniques, but may be combined into a more general class of realizations. These realizations, which are called <u>cyclo-static</u> realizations [8][9], use both parsing-in-time and parsing-in-space to generate realizations which are optimal but are neither SSIMD or systolic. From the SSIMD viewpoint, the partial parsing of the algorithm in space guarantees that a rate-optimal solution can be generated and further guarantees that the inefficient searching procedures for sub-optimal solutions will never have to be used. From the systolic viewpoint, the removal of a global clock transfer constraint and the ability to deal with more than one time index reduces the inherent inefficiency in the graph. Formally, these two approaches may be combined using the blocking technique [10][13]. This merged approach for automatically generating optimal multiprocessor realizations is currently being development [16].

One of the major components of this research effort has always been the multi-microprocessor system [2][15]. Although the primary thrust of this research is theoretical, the techniques studied are always tested and evolved in the context of the multiprocessor computer. During the past three years, this system has been evolved and extended in both hardware and software. In the hardware area, a new arithmetic processor board set, based on the TMS320 signal processing microcomputer, has been designed, laid out, and tested. This board set should substantially improve the arithmetic throughput of the overall multiprocessor. In addition, a new (the third) operating and multiprocessing debugging system has been implemented [15]. This system is much more user friendly than previous systems, and is specifically designed to handle both synchronous and asynchronous debugging problems. This system was heavily utilized in the verification of SSIMD performance [3] and the development of the SSIMD compiler [14].

The other area of DSP research which was addressed under this work unit was time-frequency signal representations [11][12][17]. In this research, a new class of filter banks were developed which allowed for both critical decimation in the frequency domain (the same number of frequency domain samples as time domain samples) and exact reconstruction in the time domain. In addition, a filter design procedure was developed which allowed for the optimal design of filter banks of arbitrary resolution while still maintaining exact reconstructability. These results are particularly important for the frequency domain coding of images and other signals.

PUBLICATIONS:

1. "Optimal Implementation of Recursive Signal Flow Graphs on Synchronous Multiprocessor Architectures," T.P. Barnwell, III, IEEE Workshop on Digital Signal Processing and VLSI, Santa Barbara, CA, Sept. 1981.

2. "A Synchronous Multi-Microprocessor System for Implementing Digital Signal Processing Algorithms," T.P. Barnwell and C.J.M. Hodges, Professional Program Session Record 21 of Southcon/82, pp. 21/4/121/4/6, March 1982 (invited).

3. Optimum Implementation of Single Time Index Signal Flow Graphs on Synchronous Multiprocessor Machines," T.P. Barnwell, III, C.J.M. Hodges, and M. Randolf, Proceedings of ICASSP '82, Paris, France, pp. 687-690, May 1982.

4. "Optimal Implementation of Signal Flow Graphs on Synchronous Multiprocessors," T.P. Barnwell, III, and C.J.M. Hodges, Professional Program Sessions Record 22 of Electro/82, June 1982 (invited).

5. "Synchronous Techniques for Signal Flow Graph Implementation," T.P. Barnwell, III, NSF Workshop on Digital Signal Processing, Washington, DC, June 1982.

6. "Optimal Implementation of Signal Flow Graphs on Synchronous Multiprocessors," T.P. Barnwell and C.J.M. Hodges, Proceedings of the 1982 International Conference on Parallel Processing, Belaire, MI, August 1982.

7. "Optimal Implementation of DSP Algorithms on Synchronous Multiprocessors," T.P. Barnwell, III, and C.J.M. Hodges, Proc. of Workshop on Algorithmically Specialized Computer Organizations, Oct. 1982.

8. "Optimal Implementation of Flow Graphs on Synchronous Multiprocessors," T.P. Barnwell, III, and D.A. Schwartz, Proceedings of Asilomar Conference on Circuits and Systems, November 1983.

9. "A Graph Theoretic Technique for the Generation of Systolic Implementations for Shift-Invariant Flow Graphs," D.A. Schwartz and T.P. Barnwell, III, Proc. ICASSP '84 San Diego, Ca., March 1984.

10. "Increasing the Parallelism of Filters Through Transformations to Block Form," D.A. Schwartz and T.P. Barnwell, III, Proc. ICASSP '84, San Diego, Ca., March 1984.

11. "A Procedure for Designing Exact Reconstruction Filter Banks for Tree-Structured Subband Coders," M.J.T. Smith and T.P. Barnwell, III, Proc. ICASSP '84, San Diego, Ca., March 1984.

12. "Exact Reconstruction Techniques for Tree-Structured Subband Coders," M.J.T. Smith and T.P. Barnwell, III, accepted for publication, IEEE Transactions on ASSP.

PAPERS IN PREPARATION:

13. "Block Filter Realizations for Increased Parallelism," D. A. Schwartz and T. P. Barnwell.

14. "An SSIMD Compiler for Signal Flow Graphs," S. H. Lee and T. P. Barnwell

THESES IN PREPARATION:

15. "A Multiprocessor System for Testing Parallel Digital Signal Processing Realization," C. J. M. Hodges (Master's Thesis, August, 1984)

16. "Optimal Implementations of Flow Graphs on Synchronous Multiprocessors," D. A. Schwartz (Ph.D. Thesis, December, 1984)

17. "Analysis-Synthesis Systems for Time-Frequency Representation," M. J. T. Smith (Ph.D. Thesis, December, 1984)

WORK UNIT NUMBER 5

TITLE: Two-Dimensional Optical Storage and Processing

SENIOR PRINCIPAL INVESTIGATOR:

Thomas K. Gaylord, Professor

SCIENTIFIC PERSONNEL:

M.G. Moharam, Assistant Professor
W.E. Baird, Instructor
C.C. Guest, Ph.D. completed December 1983 (Ph.D. Thesis entitled: Holographic Optical Digital Parallel Processing)
M.M. Mirasalehi, Graduate Research Assistant (Ph.D. candidate)
P.J. Lunsford, Graduate Research Assistant (M.S. candidate)

SCIENTIFIC OBJECTIVE:

The scientific objective of this research was to develop broadly-based, theoretical and experimental knowledge of high-capacity two-dimensional optical digital processing and two-dimensional optical information storage. This brought together a range of concepts from basic physics to signal processing in its most generalized form. Optical digital parallel processing in forms such as a word/signature detector, multiport memories, and a parallel numerical processor were investigated.

RESEARCH ACCOMPLISHMENTS:

As a part of the research sponsored by the Joint Services Electronics Program we have originated and developed a rigorous coupled-wave theory of grating diffraction. This new theory was published in July 1981.

The rigorous coupled-wave theory allows the diffraction by gratings to be analyzed without approximations. This work has allowed, for the first time, simple and accurate grating diffraction calculations to be performed. These grating structures are widely used in laser beam deflection, guidance, modulation, coupling, filtering, wavefront reconstruction, and distributed feedback in the fields of acousto-optics, holography, quantum electronics, signal processing, and spectrum analysis.

By expanding the electric field in terms of space harmonics and substituting it into the wave equation, an infinite set of second-order coupled-wave equations is produced. We have applied the state variables approach from linear systems theory to solving this set of equations. This results in closed-form expressions for the space harmonic fields in terms of the eigenvalues and eigenvectors of the differential equation coefficient matrix. By applying the electromagnetic boundary conditions, a set of linear algebraic equations is obtained. This may then be solved for the forward and backward diffracted fields outside of the grating.

The rigorous coupled-wave method of analysis is straightforward to implement numerically. It has been implemented on large computers and on minicomputers.

As a side benefit, the rigorous coupled-wave theory has been used by us to evaluate in detail, for the first time, the previous approximations (neglect of higher-order waves, neglect of second derivatives of field amplitudes, neglect of boundary effects, and neglect of dephasing) that are inherent in previous approximate theories such as 1) multiwave coupled-wave theory, 2) two-wave second-order coupled-wave theory, 3) two-wave modal theory, 4) two-wave first-order coupled-wave theory, 5) Raman-Nath theory, and 6) amplitude transmittance theory. The regimes of applicability for each of these approximate theories have now been analyzed by us.

We were invited to publish a review paper on this new theory and how it relates to previous approximate theories. This invited paper was published in the May 1982 issue of Applied Physics. Our method provides, for the first time, a straightforward method to analyze diffraction from gratings accurately. This approach has been adopted by numerous companies (I.B.M., Bausch and Lomb, Perkin Elmer, Marconi Avionics, etc), laboratories (Bell Labs, Systems Research Laboratories, Battelle Columbus Laboratories, etc.), and universities (University of Southern California, Tel-Aviv University, University of South Florida, etc.). Applications include laser beam deflection, modulation, coupling, filtering, distributed feedback, holographic beam combining, wavelength multiplexing and demultiplexing, optical digital parallel processing, acousto-optic signal processing, spectrum analysis, diffractive optics, and head-up displays. The rigorous coupled-wave analysis has been extended by us to surface-relief (corrugated) gratings. This is the case most often used in making diffractive optical elements. In addition, the theory has been extended to any general polarization incident upon the grating together with the possibility of losses in the medium. The only case that cannot be analyzed by rigorous coupled-wave theory is that of a pure reflection grating (with grating fringes parallel to the surface). We have, however, developed a rigorous chain-matrix approach to handle this case.

A patent was issued to us for "optical holographic content-addressable memory system for truth-table look-up processing." This is an extension of the basic system that we investigated under JSEP sponsorship. We have analyzed our system experimentally and theoretically to determine the probability of a false alarm and the probability of miss for the operations of addition and multiplication performed using binary and residue number systems in the presence of laser beam amplitude and phase errors. For binary-coded residue numbers, the operations of 4-, 8-, 12-, and 16-bit addition and multiplication were treated. The minimum probability of error that can be achieved and the corresponding detector threshold settings were determined in each case allowing for the effects of Gaussian distributions in the amplitude and the phase in the recording beams. Resultant probabilities of error for practical conditions (10^{-6}) were found to be very competitive with those from state-of-the-art nonparallel technologies.

Research into the logical reduction of truth-tables for both look-up optical processors and VLSI programmable logic arrays was partially completed. A program written in APL was generated to determine the minimum number of logical function minterms for each output bit that are needed for addition and multiplication using binary and residue arithmetic.

For the residue number system, the logically minimized numbers of input combinations needed for each operation were determined for moduli 2 through 23. The moduli sets that require the minimum number of reference patterns were determined for addition and multiplication of 4-, 8-, 12-, and 16-bit words. This very important information has been accepted for publication in the IEEE Transactions on Computers.

PUBLICATIONS AND PRESENTATIONS:

[1] Weaver, J. E. and Gaylord, T. K., "Evaluation Experiments On Holographic Storage of Binary Data in Electro-Optic Crystals," Optical Engineering, vol. 20, pp. 404-411, May/June 1981.

[2] Gaylord, T. K., Guest, C. C., and Gaylord, E. F., "Seven-Segment Representation of Full ASCII and EBCDIC Character Sets," Computer, vol. 14, pp. 102-103, August 1981.

[3] Gaylord, T. K. and Moharam, M. G., "Thin and Thick Gratings: Terminology Clarification," Applied Optics, vol. 20, pp. 3271-3273, October 1, 1981.

[4] Gaylord, T. K., Guest, C. C., Moharam, M. G., and Weaver, J. E., "Holographic Data Processing Applications Using Photorefractive Crystals," Ferroelectrics, vol. 35, pp. 137-142, 1981.

[5] Gaylord, T. K. and Moharam, M. G., "Interrelationships Between Various Planar Grating Diffraction Theories," (Abstract) Journal of the Optical Society of America, vol. 71, pg. 1569, December 1981.

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[9] Gaylord, T. K., "Memories, Optical Holographic," Optical Industry and Systems Directory, Pittsfield, MA, Optical Publishing Co., pp. 116-119, 1982.

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[12] Gaylord, T. K. and Moharam, M. G., "Rigorous Theory of Planar Reflection Grating Diffraction," (Abstract) Journal of the Optical Society of America, vol. 72, pg. 1824, December 1982.

[13] Moharam, M. G. and Gaylord, T. K., "Vector Three-Dimensional Theory for Planar Grating Diffraction," (Abstract) Journal of the Optical Society of America, vol. 72, pg. 1813, December 1982.

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[18] Moharam, M. G. and Gaylord, T. K., "Diffraction of Finite Beams by Dielectric Gratings," (Abstract) Journal of the Optical Society of America, vol. 73, pg. 1941, December 1983.

[19] Mirsalehi, M. M., Guest, C. C., and Gaylord, T. K., "Optical Truth-Table Look-Up Processing of Digital Data," (Abstract) Journal of the Optical Society of America, vol. 73, pg. 1951, December 1983.

[20] Baird, W. E., Gaylord, T. K., and Moharam, M. G., "Diffraction Efficiencies of Transmission Absorption Gratings," (Abstract) Journal of the Optical Society of America, vol. 73, pg. 1889, December 1983.

[21] Mirsalehi, M. M., Guest, C. C., and Gaylord, T. K., "Residue Number system Holographic Truth-Table Look-Up Processing: Detector Threshold Setting and Probability of Error Due to Amplitude and Phase Variations," Applied Optics, vol. 22, pp. 3583-3592, November 15, 1983.

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[23] Gaylord, T. K. and Guest, C. C., "Optical Interferometric Liquid Gate Plate Positioner," Review of Scientific Instruments, vol. 55, pp. xxx-xxx, 1984. (accepted).

WORK UNIT NUMBER 6

TITLE: Hybrid Optical/Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR:

William T. Rhodes, Professor

SCIENTIFIC PERSONNEL:

Mr. Joseph Mait, Graduate Research Assistant (Doctoral candidate)
Mr. Robert Stroud, Graduate Research Assistant (Doctoral candidate)
Mr. James Guske, Graduate Research Assistant (Doctoral candidate)

SCIENTIFIC OBJECTIVE:

The overall goal of this work is the development of hybrid optical/electronic techniques for 2-D signal processing that complement existing and projected digital methods. Major areas of activity include (1) a theoretical investigation and the implementation of incoherent optical systems for bipolar spatial filtering; (2) the development of hybrid optical/electronic Fourier scanning techniques for highspeed image processing; (3) the investigation of partially coherent optical methods for investigation of general hybrid techniques for shift-variant 2-D signal processing.

RESEARCH ACCOMPLISHMENTS:

Bipolar Incoherent Spatial Filtering

Incoherent optical imaging systems, appropriate for selfluminous objects or incoherently illuminated transparent objects, can be used for realtime spatial filtering applications. Unfortunately, because light intensity is a nonnegative quantity, these systems in their primative form are incapable of bipolar or complex-valued spatial filtering operations. In this research hybrid optical-electronic imaging methods for bipolar spatial filtering have been investigated. A simple example of such a method employs a two-arm imaging system where the same object is imaged simultaneously in two different ways, the resultant images being subtracted to produce the desired bipolar image distribution.

Major emphasis has been given to the development of computer methods for specifying pupil functions, which are recorded as computer holograms and placed in the apertures of the hybrid imaging systems. A unified approach to pupil function design has been developed that is applicable to all diffraction-limited two-pupil bipolar spatial filtering systems discussed in the literature. This unified approach greatly facilitates the specification of pupil functions for so-called "interactive" systems, where light from two imaging subsystems interferes, and bases the interactive-regime pupil functions on non-interactive-regime pupil functions (for which there is no light interference).

It is desirable that these pupil functions be specified so as to minimize bias in the resultant individual image distributions, since excessive bias results in a noisier synthesized bipolar image (because, for example, of bias-induced shot noise in the image detection processes). At the same time, the pupil functions must be limited in spatial dimension, spatial bandwidth, and dynamic range. (Unique pupil functions exist that truly maximize the signal-to-noise ratio of the synthesized image; however, these pupil functions are not physically realizable because of bandwidth limitations.) In order to determine synthesis procedures that are somehow optimum, local and global signal-to-bias ratios have been defined, along with measures of pupil function efficiency. Using these definitions, pupil design procedures have been developed that are optimum in the sense of minimizing image bias subject to practical constraints on pupil function specification. Iterative procedures have been developed for computer implementation, and a number of pupil functions have been determined and tested by computer simulation. Convergence properties of the procedures have been investigated theoretically and partially verified experimentally.

One benefit of this research to the signal processing community as a whole is the expansion of the scope of the theory of constrained iterative processing by the establishment for formalisms for iterative processing where multiple objectives are to be attained with dependent and/or independent constraints.

The issue of phase-only pupil functions (which correspond to high optical efficiency imaging) was studied, and it was determined that an arbitrary synthesis using only two such pupil functions was not possible. However, approximate methods for such syntheses have been found.

Partially Coherent Image Processing

We have performed what we consider to be landmark experiments demonstrating an extremely simple yet effective method for image enhancement. The basic technique involves a modification of the source distribution and the insertion of a mask in the pupil plane of a conventional incoherent imaging system. Imagery obtained from the resultant partially coherent imaging system has been of extremely high quality, particularly when compared with imagery obtained from fully coherent systems, and the enhancement of a wide variety of texture and spatial features has been shown to be possible. An example of such enhancement is the nonlinear emphasis of low-amplitude spatial bandpass structure riding on high dynamic range low spatial frequency structure. Incoherent spatial filtering cannot be used for such a task because of the autocorrelation function nature of the imaging system transfer function, and coherent spatial filtering suffers from severe noise problems.

In connection with this work we have discovered a new technique for linear-in-intensity imaging of coherent (or partially coherent) wave fields that has important implications for speckle reduction in laser radar and related fields. An important characteristic of the method, which requires dynamic modification of the imaging system aperture function, is that access to the object distribution is not required. Related study has determined spatial bandwidth conditions that must be satisfied by the object distribution for the scheme to work.

Fourier Transform Scanning Image Processing

We constructed an experimental system that projects an intensity fringe pattern of the form

$$I(x,y;t) = 1 + \cos[\omega t + 2\pi(ux + vy)]$$

that moves across an object. By measuring the a.c. component of the reflected or transmitted light power, it is possible to measure the magnitude and phase of a Fourier component of the object distribution. If only a small number of Fourier components are required, such a system can outperform a system that fully scans the object and evaluates an FFT. Proof-of-principle experiments have been performed and will be reported in the literature.

Space-Variant Image Processing

Work in this area has taken several directions. Early work concentrated on signal "format" changing isomorphisms, such as 1-D spatial to 2-D spatial or 2-D spatial to 1-D temporal frequency. In connection with this work an important link was established between space-integration and time-integration folded spectrum analysis using optical techniques. Instrumentation built for the Fourier transforming scanning system discussed above has been used to record, for the first time using time-integration techniques, the 2-D spatial frequency transform of an object that is specified in the form of a video signal. More recently a technique has been developed for slowly space-invariant parallel image processing that has significant potential for increasing resolution in photolithography for high-density integrated circuitry. The technique allows structurally differing patterns to be imaged in different ways in different regions of the circuit.

Major attention has been given to the conceptual development and analysis of algebraically-oriented opto-electronic signal processing systems for vector-matrix and matrix-matrix multiplication. Especially significant has been the invention of an optical implementation of a systolic array vector-matrix multiplier using acousto-optic technology. This development led to the development by other researchers of a high-speed opto-electronic matrix-matrix multiplier that performs with 32-bits of accuracy. Fundamental limitations on several generic processor types have been analyzed.

PUBLICATIONS AND PRESENTATIONS:

Conference Presentations (No Proceedings):

1. W.T. Rhodes, "Fourier transform scanning hybrid image processor," presented at ICO-12, Twelfth Congress of the International Commission for Optics, Graz, Austria, September 1981.

2. H.J. Caulfield and W.T. Rhodes, "Acousto-optic matrix-vector multiplication," presented at 1981 Annual Meeting of the Optical Society of America, Orlando,Florida, October 1981 (J. Opt. Soc. Am. 71, 1626 (1981) (A)).

3. W.T. Rhodes and M. Koizumi, "Linear-in-intensity imaging of coherent wave fields," 1982 Annual Meeting of the Optical Society of America, Tucson, October 1982, (J. Opt. Soc. Am. 72, 1721 (1982) (A)).

4. W.T. Rhodes, K.D. Ruehle, and R.E. Stroud, "Two-Dimensional Optical Fourier Transformation by Time-Integration Methods," 1983 Annual Meeting of the Optical Society of America, New Orleans, October 1983, (J. Opt. Soc. Am. 73, 1858 (1983) (A)).

5. J.N. Mait and W.T. Rhodes, "Minimum bias pupil design for bipolar incoherent spatial filtering," 1983 Annual Meeting of the Optical Society of America, New Orleans, October 1983, (J. Opt. Soc. Am. 73, 1858 (1983) (A)).

Conference Presentations (Proceedings):

1. J.N. Mait and W.T. Rhodes, "Iterative design of pupil functions for bipolar incoherent spatial filtering," in Processing of Images and Data from Optical Sensors, W. Carter and G. Reynolds, eds. (Proc. SPIE, Vol. 292 (1981), pp. 66-72.

2. H.J. Caulfield and W.T. Rhodes, "Optical implementation of systolic array processing," in Optical Information Processing for Aerospace Applications," NASA Conference, Langly, October 1981, NASA Conference Publication No. 2207.

3. A. Tarasevich, N. Zepkin, and W.T. Rhodes, "Matrix-vector multiplier with time-varying single dimensional spatial light modulators," in Optical Information Processing for Aerospace Applications, NASA Conference, Langly, October 1981, NASA Conference Publication No. 2207.

4. W.T. Rhodes, "Acousto-optic matrix-vector and matrix-matrix multiplication," in Proceedings of BMD/ATC Technical Interchange Meeting, Application of Opto-Electronics, La Jolla, March 1982.

5. J.N. Mait and W.T. Rhodes, "Dependent and independent constraints for a multiple objective iterative algorithm," in Signal Recovery and Synthesis with Incomplete Information and Partial Constraints (Technical Digest) (Optical Society of America, 1983), pp. THA14-1 through THA14-4.

6. W.T. Rhodes, A. Tarasevich, and N. Zepkin, "Complex covariance matrix inversion with a resonant electro-optic processor," in Two-Dimensional Image and Signal Processing, G. Morris, ed. (Proc. SPIE, Vol. 388, 1983), pp. 197-204.

7. W.T. Rhodes and M. Koizumi, "Image enhancement by partially coherent imaging," in Proceedings of the 10th International Optical Computing Conference (IEEE Computer Society, 1983, IEEE Order No. 83CH1880-4), pp. 32-35.

8. W.T. Rhodes, "Hybrid time- and space-integration method for compute holography," in International Conference on Computer-Generated Holography, S. Lee, ed. (Proc. SPIE, Vol. 437, 1983), pp. xx-xx.

9. W.T. Rhodes, "Acousto-optic algebraic processors," in Real-Time Signal Processing VI, K. Bromley, ed. (Proc. SPIE, Vol. 431, 1983), pp. xx-xx.

10. H.J. Caulfield and W.T. Rhodes, "Optical algebraic processing architectures and algorithms," in Optical Computing, J.A. Neff, ed. (Proc. SPIE, Vol. 456, 1984), pp. xx-xx.

Journal Publications:

1. W.T. Rhodes, "Acousto-optic signal processing: convolution and correlation," Proc. IEEE 69, 64-79 (1981).

2. H.J. Caulfield, W.T. Rhodes, M.J. Foster, and S. Horvitz, "Optical implementation of systolic array processing," Opt. Commun. 40, 86-90 (1981).

3. H.J. Caulfield, J.A. Neff, and W.T. Rhodes, "Optical computing: the coming revolution in optical signal processing," Laser Focus/Electro-Optics Magazine, November 1983, pp. 100-110 (invited).

4. W.T. Cathey, B.R. Frieden, W.T. Rhodes, and C.K. Rushforth, "Image gathering and processing for enhanced resolution," J. Opt. Soc. Am. A1, 241-250 (1984).

5. W.T. Rhodes and P.S. Guilfoyle, "Acousto-optic algebraic processing architectures," Proc. IEEE 72, 820-830 (1984) (invited).

Chapter in Books;

1. W.T. Rhodes and A.A. Sawchuk, "Incoherent Optical Processing, in Optical Information Processing: Fundamentals, S. Lee, ed. (Springer-Verlag, New York, 1981).

2. W.T. Rhodes, "The Falling Raster in Optical Signal Processing," in Transformation in Optical Signal Processing, W. Rhodes, J. Fienup, and B. Saleh, eds. (SPIE, Bellingham, 1982).

3. W.T. Rhodes, "Space-Variant Processing," in Applications of the Optical Fourier Transform, H. Stark, ed. (Academic Press, New York, 1982).

WORK UNIT NUMBER 7

TITLE: Electromagnetic Measurements in the Time Domain

SENIOR PRINCIPAL INVESTIGATOR:

G.S. Smith, Associate Professor

SCIENTIFIC PERSONNEL:

J.D. Nordgard, Professor
L.N. An, Graduate Research Assistant (Ph.D. 1981)
W. Scott, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The broad objective of this research is to develop new methodology for making electromagnetic measurements directly in the time domain or over a wide bandwidth in the frequency domain. This research includes the development of theoretical analyses necessary to support the measurement techniques. One aspect of the research is the systematic study of radiating structures placed near or embedded in material bodies. In a practical situation the radiator might serve as a diagnostic tool for determining the geometry, composition or electrical constitutive parameters of the body.

RESEARCH ACCOMPLISHMENTS:

Antennas Near a Material Interface

The directive properties of antennas for transmission into a material half space were investigated. In a practical situation, the antennas might be located in the air with the directive transmission into the earth. The initial theoretical and experimental investigations were for a canonical problem: the circular-loop antenna of general size parallel to a planar interface [1]. The investigation was later extended to treat a coaxial array of circular loops parallel to the interface [2]. This work showed that a single loop or an array of loops in a dielectric half space 1 could have a very directive field pattern into the adjacent dielectric half space 2, the directively at a point directly below the loop increasing with the ratio of permittivities $\varepsilon_2/\varepsilon_1$. The directivity has a peak when the loop is close to the interface.

A general analysis, based on the plane wave spectral representation of the electromagnetic field, was developed to explain the directive properties of antennas, like the circular loop, over a material half space [3]. This analysis provides a general physical interpretation of the factors that increase the directive properties of an antenna when it is placed over a material half space.

Measurement of Electrical Constitutive Parameters of Materials Using Antennas

The use of antennas as diagnostic probes for measuring the electrical constitutive parameters of materials is being investigated. Techniques have been developed to obtain the parameters $\sigma(\omega)$ and $\varepsilon(\omega)$ (electrical conductivity and permittivity) from the measured terminal admittance of a monopole antenna immersed in the material. Different algorithms were derived for antennas that are electrically small and for those of general electrical length. A measurement program to verify these techniques is now in progress.

Miniature Electric-Field Probes

A common design for miniature electric-field probes consists of an electrically short antenna with a diode across its terminals; a resistive, parallel-wire transmission line transmits the detected signal from the diode to the monitoring instrumentation. Small dipoles are desirable because they provide high spatial resolution of the field, and because they permit a frequency-independent response at higher microwave frequencies. Recent efforts have produced probes with dipole half lengths h less than one millimeter. With the advances occuring in microelectronics and thin-film technology, the construction of even smaller probes may be possible.

This research examined the limitations imposed on the sensitivity of the probe by a reduction in its physical size [5]. A model that contains noise sources for the diode and the resistive transmission line was used to obtain the signal-to-noise ratio for the probe, and this was examined as a function of the parameters that describe the dipole, diode, resistive transmission line and amplifier. When the physical dimensions of the probe are reduced by the scale factor $k_\ell (k_\ell < 1)$, the signal signal-to-noise ratio is found to decrease by approximately the factor k_ℓ^{-2}. A numerical estimate was made for the sensitivity of miniature probes with dipole half lengths in the range $10\ \mu m < h < 1$ cm.

This work was also supported by the National Science Foundation.

PUBLICATIONS AND PRESENTATIONS:

Conference Publications (Proceedings)

1. L.N. An and G.S. Smith, "The circular-loop antenna near a material interface," 1981 IEEE Antennas and Propagation Society International Symposium and National Radio Science Meeting (URSI), Los Angeles, CA, pp. 537-540, June 1981.

2. G.S. Smith and L.N. An, "Loop antennas for directive transmission into a material half space," 1982, IEEE Antennas and Propagation Society International Symposium and National Radio Science Meeting (URSI), Albuquerque, NM, pg. 81, May 1982.

3. G.S. Smith, "Directive properties of antennas for transmission into a material halfspace," 1983 IEEE Antennas and Propagation Society International Symposium and National Radio Science Meeting (URSI), Houston, TX, pg. 7, May 1983.

4. G.S. Smith, "Limitations on the size of miniature electric field probes-the smallest dipoles," 1984 IEEE Antennas and Propagation Society International Symposium and National Radio Science Meeting (URSI), Boston, MA, to be presented, June 1984.

Journal Publications

1. L.N. An and G.S. Smith, "The Horizontal Circular Loop Antenna Near a Planar Interface," Radio Science, volume 17, no. 3, pp. 483-502, May-June 1982.

2. G.S. Smith and L.N. An, "Loop Antennas for Directive Transmission into a Material Half Space," Radio Science, volume 18, no. 5, pp. 664-674, Sept.-Oct. 1983.

3. H.I. Bassen and G.S. Smith, "Electric Field Probes - A Review," (Invited Paper), IEEE Trans. Antennas and Propagation, volume AP-31, no. 5, pp. 710-718, Sept. 1983.

4. G.S. Smith, "Directive Properties of Antennas for Transmission into a Material Half Space," IEEE Trans. Antennas and Propagation, volume AP-32, no. 3, pp. 232-246, March 1984.

5. G.S. Smith, "Limitations on the Size of Miniature Electric Field Probes," IEEE Trans. Microwave Theory and Techniques, volume MTT-32, no. 6, June 1984, to be published.

Publications in Books

1. G.S. Smith, "Loop Antennas," in Antenna Engineering Handbook, (R.C. Johnson and H. Jasik, Eds.), New York: McGraw-Hill, pp. 5-1 to 5-24, 1984.

Theses

1. L.N. An, "The eccentrically insulated circular-loop antennas and the horizontal circular-loop antennas near a planar interface," Ph.D. Thesis. Georgia Institute of Technology, Atlanta, Georgia, June 1981, 192 pages.

WORK UNIT NUMBER 8

TITLE: Automated Radiation Measurements for Near and Far-Field Transformations.

SENIOR PRINCIPAL INVESTIGATOR:

Edward B. Joy, Professor

SCIENTIFIC PERSONNEL:

G.K. Huddleston, Associate Professor
W.M. Leach, Jr., Associate Professor
T.E. Brewer, Instructor
L.E. Corey, Graduate Research Assistant (Ph.D., December 1980)
B.E. Eisenman, Graduate Research Assistant (M.S., December 1981)
T.G. Picard, Graduate Research Assistant (M.S., June 1981)
R.E. Wilson, Graduate Research Assistant
G.R. Scott, Graduate Research Assistant (M.S., June 1982)
J.M. Rowland, Graduate Research Assistant
K. Hsu, Graduate Research Assistant (M.S., June 1983)

SCIENTIFIC OBJECTIVES:

The objectives of this work are:

1. Development of a general theory for probe position error compensation for near field measurements performed on arbitrary surfaces.

2. Development of an indirect measurement method to determine the fields on the surface of a dielectric shell enclosing a radiating antenna to serve as an analytical tool in isolating deficiencies in analysis methods.

3. Development of a computationally efficient near field coupling equation between a test antenna and a measuring probe when the probe is used to sample the field radiated by the test antenna over the surface of a sphere.

RESEARCH ACCOMPLISHMENTS:

An approximate technique for planar surface probe position error was formulated, computer implemented and demonstrated. Accuracy for small probe position errors was shown to be very good. This approximate technique known as "K-correction" is a phase only correction and based on the assumption of all near field energy propagating in the K-direction of the main beam peak. This technology was transferred to the RCA, U.S. Navy Aegis program and is now in use. Alignment of the Aegis phased array was judged impossible without this technology.

A spherical surface probe position error compensation technique was developed which includes both amplitude and phase correction based on radial field propagation only. This simplified technique, which in the limit as the radius of the measurement sphere becomes large with respect to the diameter of the antenna under test is accurate, was shown by computer simulation to be very effective and easily to implement in spherical surface near field measurement systems.

Sufficient and efficient spherical surface sampling requirements have been investigated. The required number of near field samples was found to be larger than generally used. New sample spacing requirements were published and tested via computer simulation.

During the first year, development of radome analysis methods was continued from earlier work based on geometrical optics for the determination of the fields on the surface of a dielectric shell enclosing a radiating antenna. First-order reflections from the radome wall are now included in the analysis, and dielectric constant variations over the radome volume, as may be caused by aerodynamic heating, are also modelled. Significant aperture antenna synthesis work has also been done to accurately characterize the near fields of actual antennas from measured far-field principal plane patterns. Comparisons of predicted and measured radome performance have been done to further clarify deficiencies in current analysis methods. Polarimetric effects of radomes have also been studied.

Efforts during the second and third years have been directed toward the completion of the Automated Radiation Laboratory to support spherical near-field and far-field radiation measurements. All positioner equipment has been installed and successfully interfaced to the microcomputer so that automatic positioning of the test antenna in the spherical measurement coordinate system is an accomplished fact. The Klystron microwave signal source has been frequency stabilized using an EIP locking frequency counter, and all microwave waveguide has been installed so that measurement of the antenna responses using the network analyzer is also an accomplished fact. In addition, the computer interface circuits required for the analog-to-digital conversion of the network analyzer signals have also been completed and are undergoing final testing. Software has been prepared to calibrate and demonstrate the automated capabilities of the facility, and this demonstration is now included as part of official guided tours of the School of EE. Although additional software modifications may be required to do specific measurements, the Automated Radiation Laboratory is essentially complete for use in support of the research proposed for the next three years.

A new formulation of the electromagnetic coupling equation between a test antenna and a near-field measuring probe has been derived for the spherical near-field measurement geometry. Although based on vector electromagnetic theory, the new formulation uses spherical scalar wave functions rather than the much more complicated vector wave functions that have been used in other formulations. This considerably reduces the complexity of the coupling equation for the spherical surface because the required addition theorems for the scalar wave functions are much less complicated than those for the vector wave functions. The basic approach uses plane wave spectrum expansions of the fields in the derivation of the coupling equation. The equation is then solved by making spherical tesseral harmonic expansions of the plane wave spectrum functions. It is shown that if the measuring probe is not too directive (which is the usual case), then probe correction requires only a knowledge of the complex polarization ratio of the probe. This work has been documented and submitted to the IEEE Transactions on Antennas and Propagation for consideration for publication.

Additional detail of these results are contained in the following publications and presentations:

Books:

1. G.K. Huddleston and H.L. Bassett, "Radomes," Chapter 44, Antenna Engineering, Johnson & Jasik, (Eds.), McGraw-Hill Book Company, 1984.

2. E.B. Joy, "TV Receiving Antennas," Chapter 29, Antenna Engineering Handbook, Johnson & Jasik, (Eds.), McGraw-Hill Book Company, 1984.

Monographs/Short Course Texts:

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1. E.B. Joy, "Antenna Measurements," Case Western Reserve University, Cleveland, OH, April 27, 1981.

2. E.B Joy, "Applications of Near Field Antenna Measurements to Phased Array Antennas," Laboratory for Research and Development in Electronics, Bangalore, India, December 6, 1982.

3. E.B. Joy, "Applications of Near Field Antenna Measurements to Phased Array Antennas," D.L.R.L., Hyderabad, India, December 7, 1982.

4. E.B. Joy, "Near Field Antenna Measurements," Indian Institute of Technology/Department of Electronics, New Dehli, India, December 16, 1982.

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